Annual Project Summary

Field Evaluation of Liquefaction Resistance at Previous Liquefaction Sites in Southern California

Grant Number: 04HQGR0073

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Program Element: PT

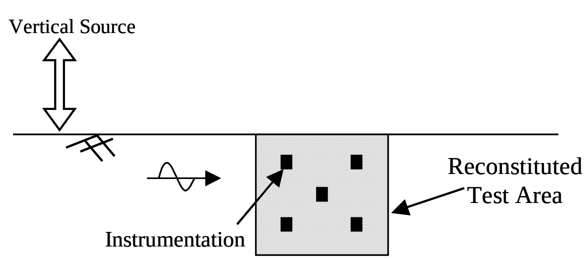
Keywords: Liquefaction, Site Effects, Strong Ground Motion

Investigations Undertaken

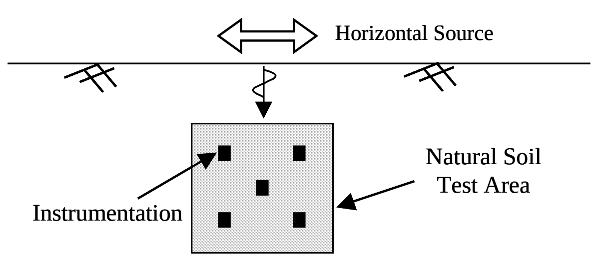
At this time, no field methods are available to the earthquake engineering profession that can be used to determine directly the liquefaction resistance of soil deposits in situ. Available techniques for evaluating liquefaction resistance include identifying potentially liquefiable deposits based on geological criteria, empirical correlations that relate liquefaction susceptibility with field test parameters, and laboratory tests on high quality or reconstituted samples that directly measure the liquefaction characteristics of the soil. Unfortunately, these procedures have disadvantages related to their simplicity, their indirect nature when empiricism is used, and sample disturbance when laboratory testing is involved.

Over the past four years, development of a field method that can be used to directly measure the liquefaction resistance of granular soils has been underway at the University of Texas at Austin (UT). The in-situ dynamic liquefaction test is designed to measure pore water pressure generation in situ without having to wait for an earthquake. The cyclic loading for the test is provided by a vibroseis, which is a large, mobile, hydraulic, shaker that is commonly used in the geophysical exploration industry. The vibroseis is used to load the ground surface and induce shaking in an instrumented soil deposit. The level of shaking is controlled by specifying the vibration levels for the vibroseis. The stress waves induce cyclic shear strains which, in turn, generate excess pore water pressure in the test area. One benefit of the test method is that cycling can be performed over a wide range in strains so that the strain level at which excess pore water pressures begin to be generated, called the cyclic threshold strain (g_t^c), can be evaluated.

Work on the test method is currently in its second stage of development. In the first stage, liquefaction of a large-scale (1.7-m^3), reconstituted, test specimen was successfully accomplished in the field with Rayleigh-type surface waves. A simplified schematic of the first-generation in situ liquefaction test configuration is shown in Figure 1a. The second-generation testing procedure differs from the first-generation procedure in terms of modifications to the testing configuration (refer to Figure 1b), loading soil in its natural (rather than reconstituted) state, and improvements to the dynamic source and instrumentation. Much of the past year has been devoted to making these second-generation advancements which are discussed in detail below.



a. First-Generation Configuration



b. Second-Generation Configuration

Figure 1 Simplified first- and second-generation in situ liquefaction test configuration.

Results

Improvements to Testing Configuration and Dynamic Source

Vertically propagating shear waves are the primary component of earthquake ground motions responsible for initiating soil liquefaction. However, the first-generation in situ liquefaction research was limited to the use of Rayleigh waves for dynamic loading. This was not ideal, but was necessitated by the limitation of the available vibroseis truck to operate only in the vertical direction. One of the key developments in the second-generation dynamic in-situ liquefaction test is the development of a new tri-axial vibroseis truck. The investigators have developed a unique, large-scale, mobile shaker as part of their National Science Foundation project in the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES). The mobile shaker, called T-Rex, weighs 29,000 kg (64,000 lb), is hydraulically operated, and capable of shaking in three orthogonal directions (X, Y or Z directions). T-Rex can generate vertically propagating shear waves by operating in the horizontal modes with peak cyclic forces as large as 133 kN (30,000 lb). A picture of T-Rex is shown in Figure 2. The ability to use a horizontal source, producing vertically propagating shear waves, allows for use of the second-generation test configuration shown in Figure 1b. This test configuration will more closely simulate actual earthquake loading during soil liquefaction which primarily involves vertically propagating shear waves.

Over the past year, several important modifications have been made to T-Rex. The first, and most important, is the modification made to the base-plate, hold-down force. The hold-down force applied to the base plate can now be incrementally increased. This capability is an important part of the present USGS-funded project because variable confining pressures in the natural soil test area are required in characterizing the soil. Pressures directly under the base-plate may be adjusted from approximately 0.7 kPa (0.1 psi) to 38 kPa (5.5 psi). This will allow for the study of in situ liquefaction triggering at various confining pressures without needing to move the embedded instrumentation deeper in the soil deposit. The second major improvement is associated with the hydraulic ram on the back of T-Rex that is used to install instrumentation in the ground. As part of this project, the ram has been outfitted with connections that are appropriate for both pushing the liquefaction sensors into place and then pulling them out upon completion of the test.

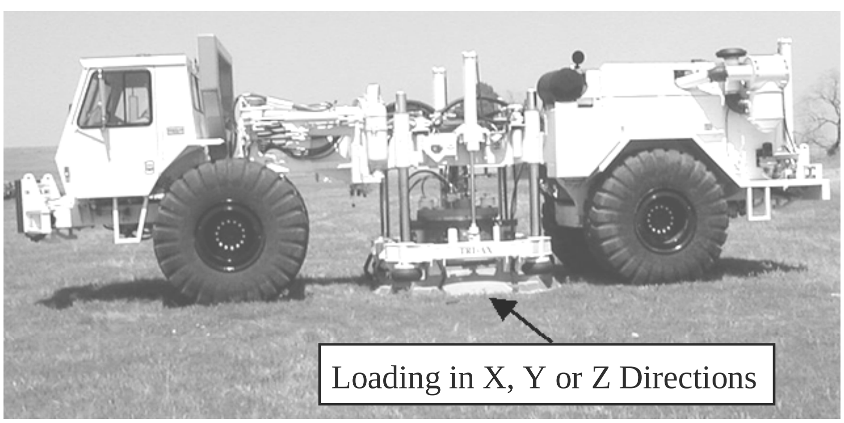


Figure 2 Photograph of T-Rex during preliminary field trials.

These important advances will allow for in situ liquefaction testing of natural soil deposits under various confining pressures using vertically propagating shear waves. The second-generation field method will be applied at two or three sites in Southern California where liquefaction has been documented. While the exact sites have not been chosen yet, sites such as Kornbloom, Radio Tower, and Heber Road in Imperial Valley are prime candidates. (These sites will be selected in January, 2005.) The ability to gain access to the sites will be a major controlling factor in site selection, so seven potential sites were originally identified. The principal investigator has been an active participant in field and laboratory studies associated with each of the seven liquefaction sites after either the 1979 Imperial Valley earthquake or the 1981 Westmorland earthquake. The wealth of field penetration and seismic testing data, as well as laboratory cyclic triaxial testing results, from the sites will permit an in-depth comparison of the behavior evaluated with the new field method and behavior predicted by empirical correlation procedures and laboratory results.

Improvements to Instrumentation

To evaluate shear strain and pore water pressure in situ, a new liquefaction test sensor has been developed. The purpose of the liquefaction test sensor is to measure soil particle motion and pore water pressure at the same location. Because particle motion and pore pressure are measured by MEMS (Micro-ElectroMechanical Systems) accelerometers and PPTs (pore pressure transducers), respectively, these two types of sensors must be combined. There are several issues that were considered in the design. First, the sensor must be small enough to avoid significant interference with the surrounding soil. Second, the unit weight of the sensor package must be similar to the total unit weight of the surrounding soil to avoid floating or sinking of the sensor after significant excess pore water pressure generation. Third, the stiffness of the sensor must be large enough to withstand the stresses during installation and dynamic loading. Fourth, the noise level needs to be small for accurate monitoring and robust data reduction. Fifth, the sensor must be able to be installed vertically from the ground surface. Finally, the sensor and cable must be waterproof.

First-generation liquefaction sensors used 28-Hz velocity transducers (geophones) to measure soil particle response during dynamic loading. While not ideal for testing at low frequencies (less than 20 Hz), the 28-Hz geophone was selected based on its compact size and its ability to perform optimally at any angular orientation. The 28-Hz geophones performed adequately for the first-generation liquefaction testing where the loading frequencies were in the 20 Hz range. In order to investigate liquefaction in the frequency range more characteristic of earthquake ground motions, it is desired to perform in-situ liquefaction tests at frequencies less than 10 Hz. The 28-Hz geophones will not allow this since their output is greatly diminished at frequencies less than 10 Hz. Therefore, to extend the scope of the in-situ liquefaction research, a sensor is needed that will allow testing at these lower frequencies. Geophones with lower natural frequencies and higher sensitivities are not an option for the liquefaction sensors due to their large size and restrictive tilt requirements (lower frequency geophones must operate within a few degrees of their stated vertical or horizontal orientation). The tilt requirements of these geophones are of particular concern since the liquefaction sensors will have a tendency to wander as they are pushed into place from the ground surface.

MEMS accelerometers offer a unique solution to the problems described above. MEMS are capacitance based accelerometers (as opposed to piezoelectric or mass balance accelerometers) that allow for response to DC accelerations as well as dynamic vibrations. This range means that, unlike traditional accelerometers, MEMS accelerometers are capable of sensing very low frequency excitation and even static tilt. Figure 3 shows a comparison of the output of a MEMS accelerometer and a 28-Hz geophone used in the first-generation liquefaction sensors. Both vibration devices were tested simultaneously with the same input motion. As can be seen, the MEMS output is much larger over the entire frequency range. At 10 Hz, the MEMS output is more than 10 times the output from the 28-Hz geophone and at 5 Hz the

MEMS output is more than 20 times greater. The addition of MEMS accelerometers allows testing in the low-frequency range that was previously impossible. Therefore, time was spent on this project to improve the liquefaction sensor. Figure 4 shows the results from a tilt calibration performed on a MEMS. The change in output voltage is referenced from the static voltage reading obtained at zero degrees tilt and 1g of acceleration (gravity). As the sensor tilts, its output voltage changes proportionally to the tilt angle. In this manner even small degrees in tilt can be monitored by the sensor. Monitoring the tilt of the liquefaction sensor is beneficial in at least three ways: (1) it allows tracking the sensor as it is pushed in the ground to determine its final location and orientation, (2) it allows determining whether the sensor moves during liquefaction of the soil, and (3) it allows the three recorded components to be resolved into their proper vertical and horizontal planes for data analysis. None of these important aspects can be done with any other vibration sensing device. Perhaps the most desirable feature of the MEMS is its compact size. Figure 5 shows a three-component MEMS accelerometer manufactured by Silicon Designs, Inc. As can be seen, it is a small device that measures approximately 2.5 cm^3 (1 $in.^3$). This compact size actually allows for a second-generation 3-D sensor that is smaller than the first-generation 2-D sensor that used 28-Hz geophones.

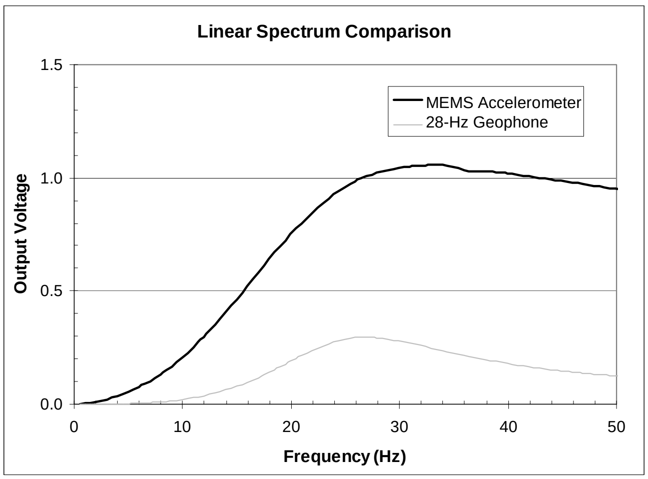


Figure 3 Comparison of the raw output voltage between a MEMS accelerometer and a 28-Hz geophone. Both sensors were tested simultaneously with the same input motion.

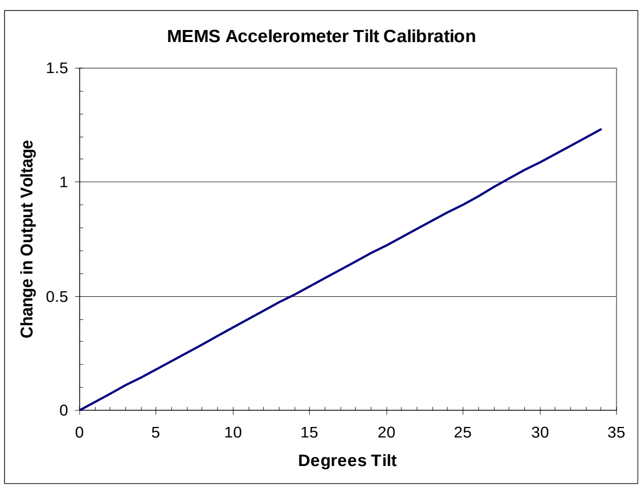


Figure 4 Results from a tilt calibration performed on a MEMS accelerometer. The change in output voltage is referenced from the static voltage reading obtained at zero degrees tilt and 1g of acceleration.

Figure 5 Three-component MEMS accelerometer used in the second-generation liquefaction sensor.

First-generation liquefaction sensors used miniature PPTs in which the reference side of the pressure-sensing diaphragm (the side opposite to the water contact surface) was vented to the atmosphere. This configuration eliminates any static pressure difference due to minor changes in atmospheric pressure. A tiny Teflon tube that extended from the back of the PPT to the electrical cable was used to vent the PPTs. Venting was achieved through the void space inside the electrical cable, which was open to the air at the end. This configuration worked adequately for short durations when the sensor was submerged in saturated soil. However, under prolonged use, it is suspected that water seeped through the electrical cable and filled the vent tube. In some instances this shorted the PPT, causing its complete destruction. In other instances, its reference to the atmosphere was blocked, making it impossible to measure accurate static pore pressure levels. Therefore, in order to make the second-generation liquefaction sensor more robust, a sealed version of the miniature PPT was acquired. Figure 6 shows a sealed version of a miniature PPT manufactured by Entran Devices, Inc. It is approximately 2.5 cm (1 in.) long. Sealed PPTs are not vented to the atmosphere and therefore fluctuate with changes in barometric pressure. This does not affect the dynamic response of the transducer because changes in barometric pressure occur very slowly and are insignificant during the time interval of dynamic loading. However, in order to measure accurate static pore pressures, the barometric pressure difference between the time of calibration and the time of the measurement must be taken into account.

A cylindrical acrylic case with a cone tip houses the MEMS accelerometer and the miniature PPT. The acrylic case is waterproof and provides protection for the enclosed components. This total package is referred to as the second-generation liquefaction sensor and is shown in Figure 7. It is 14 cm (5.5 in.) long, 3.8 cm (1.5 in.) in diameter and has an approximate unit weight of 2.24 g/cm^3 (140 pcf). The case is also fitted with a small porous bronze filter that protects the sensing diaphragm of the PPT. A six-pair cable and a small wire rope extend from the top of the case. The electrical cable provides power to the transducers and caries their signals back to the ground surface. The wire rope is used to help retrieve the sensor when testing is completed. The cable and wire rope are threaded through hollow rods that are used to push the sensor to the desire location within the natural soil test area. Slots in the aluminum top cap allow the sensor to maintain orientation as it is pushed into place. When the sensor reaches its destination the push-rods are decoupled, allowing it to move unrestricted.

Figure 6 Miniature, sealed PPT used in the second-generation liquefaction sensor.

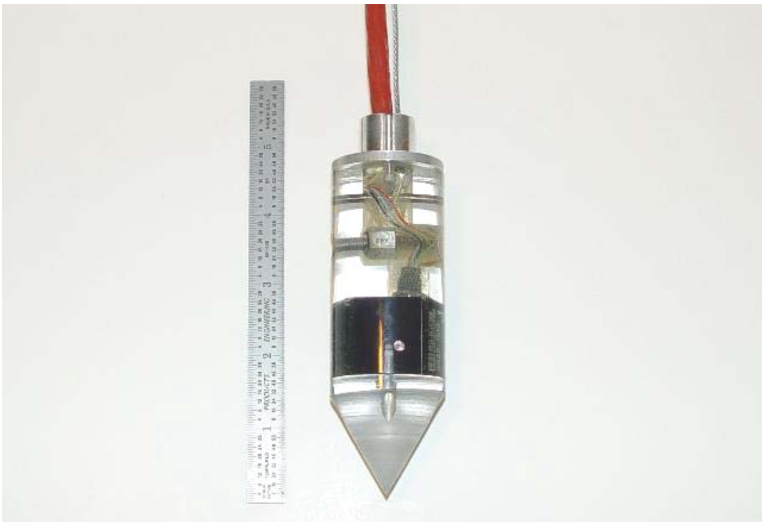


Figure 7 Completed second-generation liquefaction sensor.

Conclusions

Work on the in situ dynamic liquefaction test method is currently in its second stage of development. The past year has been devoted to improving the dynamic source and liquefaction instrumentation. These advancements will enable testing of natural soil deposits in a configuration that more closely mimics that of real earthquake loading. The liquefaction test sites will be selected in January, 2005 and field testing will be conducted before June, 2005. The research will have a significant impact in geotechnical earthquake engineering and will reduce earthquakes losses by: 1) improving field testing procedures, 2) advancing the state of knowledge regarding liquefaction, and 3) refining and validating laboratory-based procedures for liquefaction evaluation. With these improvements, potential hazards associated with liquefaction during future earthquakes can either be avoided or remediated, thus reducing earthquake losses associated with soil liquefaction.

Non-Technical Summary

At this time, no field methods are available to the earthquake engineering profession that can be used to determine directly the liquefaction resistance of soil deposits in situ. Over the past four years, development of a field method that can be used to directly measure the liquefaction resistance of granular soils has been underway at the University of Texas at Austin (UT). The in-situ dynamic liquefaction test is designed to measure pore water pressure generation in situ without having to wait for an earthquake. This field method will soon be applied at two or three sites in Southern California where liquefaction was documented in previous earthquakes. Testing at these sites represents a necessary step in validating the new field liquefaction method.

Reports Published

None to date.

Paper to be Published

None to date.

Availability of Processed Data

Once testing is completed, all data will be made available. The contact person is Professor Kenneth H. Stokoe, II. He can be reached at 512-471-4929 and by e-mail at k.stokoe@mail.utexas.edu.